

Reproducing $Z_c(3900)$ through the ISPE mechanism

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Being stimulated by the recent BESIII observation of a charged charmonium-like structure $Z_c(3900)$, in this work we study the distributions of the $J/\psi\pi^\pm$ and $\pi^+\pi^-J/\psi$ invariant mass spectra of the $Y(4260) \rightarrow \pi^+\pi^-J/\psi$ decays by the initial single pion emission (ISPE) mechanism, where the interference effects of ISPE mechanism with two other decay modes are also taken into account. The obtained $d\Gamma(Y(4260) \rightarrow \pi^+\pi^-J/\psi)/dm_{J/\psi\pi^\pm}$ and $d\Gamma(Y(4260) \rightarrow \pi^+\pi^-J/\psi)/dm_{\pi^+\pi^-}$ marvelously agree with the BESIII data to reproduce the $Z_c(3900)$ structure.

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Very recently the BESIII Collaboration announced the observation of a charged charmonium-like structure $Z_c(3900)$, which is near the $D\bar{D}^*$ threshold and comes from the analysis of the $J/\psi\pi^\pm$ invariant mass spectra in $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ at $\sqrt{s} = 4260$ MeV [1]. Before this interesting and important experimental observation, there have been some theoretical predictions of charged charmonium-like structures near $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds [2–4], which were mentioned in the BESIII paper on $Z_c(3900)$ [1].

The BESIII's result on $Z_c(3900)$ has also inspired extensive discussions on its properties [5–12] and the prediction of a charged charmonium-like structure with hidden-charm and open-strange [13]. What is more important is that the Belle Collaboration confirmed $Z_c(3900)$ in $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ at $\sqrt{s} = 4260$ MeV [14]. Later, the former CLEO-c group analyzed the data of their own and observed the charged $Z_c(3900)$ structure in their analysis of 586 pb^{-1} data taken by their detector at $\psi(4160)$ [15], which is well consistent with the BESIII's observation [1]. In addition, the neutral $Z_c(3900)$ was also released at a 3σ significance [15].

Among many theoretical papers [2–4] on the predictions of charged charmonium-like structures cited in BESIII's paper [1], Ref. [2] has given the predictions of enhancement structures near $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds in the corresponding $J/\psi\pi^+$, $\psi(2S)\pi^+$ and $h_c(1P)\pi^+$ invariant mass spectra, where $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, and $Y(4260)$ decays into $\pi^+\pi^-J/\psi$, $\pi^+\pi^-\psi(2S)$, and $\pi^+\pi^-h_c(1P)$ via the initial single pion emission (ISPE) mechanism [16], which was first proposed to understand the Belle's observations of two charged bottomonium-like structures $Z_b(10610)$ and $Z_b(10650)$ appearing in the hidden-bottom dipion decays of $\Upsilon(5S)$ [17]. Later, the ISPE mechanism was applied to study the hidden-bottom dipion decays of $\Upsilon(11020)$, where the charged bottomonium-like structures near the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds were predicted [18]. In addition, two charged strangeonium-like structures observable in the $Y(2175) \rightarrow$

$\pi^+\pi^-\phi(1020)$ process were predicted in Ref. [19] using the ISPE. These abundant theoretical results predicted by the ISPE mechanism [2, 18, 19] can be further tested in experiment.

Having more experimental information on the distribution of the $J/\psi\pi^\pm$ and $\pi^+\pi^-J/\psi$ invariant mass spectra of $Y(4260) \rightarrow \pi^+\pi^-J/\psi$ [1, 14, 15], we can perform an in-depth study of $Y(4260) \rightarrow \pi^+\pi^-J/\psi$ through the ISPE mechanism to get deeper understanding of a $Z_c(3900)$ structure discovered in the $J/\psi\pi^\pm$ invariant mass spectrum. Along this road, in this paper we will fit our model based on the ISPE mechanism to the experimental data of the $J/\psi\pi^\pm$ and $\pi^+\pi^-J/\psi$ invariant mass spectra of $Y(4260) \rightarrow \pi^+\pi^-J/\psi$. In this study, we would like to check whether $Z_c(3900)$ structure can be reproduced through the ISPE mechanism. This will be helpful to deeply understand how to generate $Z_c(3900)$, which makes our study presented here an intriguing research work.

As for the hidden-charm dipion decay discussed here,

$$Y(4260)(p_0) \rightarrow \pi^+(p_1)\pi^-(p_2)J/\psi(p_3),$$

there exist different decay mechanisms as shown in Fig. 1, which play an important role to connect the initial state $Y(4260)$ and final state $\pi^+\pi^-J/\psi$. Among these decay mechanisms, the first one is due to the $Y(4260)$ direct decay into $\pi^+\pi^-J/\psi$ (see Fig. 1 (a)), where $Y(4260) \rightarrow \pi^+\pi^-J/\psi$ occurs without the intermediate state contribution and mainly provides the background for the distributions of the $\pi^+\pi^-$ and $J/\psi\pi^\pm$ invariant mass spectra. The intermediate state contributions come from $\sigma(600)$, $f_0(980)$, and the triangle hadronic loops composed of charmed mesons.

By the effective Lagrangian approach, the decay amplitude of the direct decay of $Y(4260) \rightarrow \pi^+\pi^-J/\psi$ can be written as

$$\begin{aligned} \mathcal{M}_{\text{Direct}}[Y(4260) \rightarrow \pi^+\pi^-J/\psi] &= \frac{F}{f_\pi^2} \epsilon_{Y(4260)} \cdot \epsilon_{J/\psi} \left\{ \left[q^2 - \kappa(\Delta M)^2 \left(1 + \frac{2m_\pi^2}{q^2} \right) \right]_{\text{S-wave}} \right. \\ &\quad \left. + \left[\frac{3}{2} \kappa((\Delta M)^2 - q^2) \left(1 - \frac{4m_\pi^2}{q^2} \right) \left(\cos \theta^2 - \frac{1}{3} \right) \right]_{\text{D-wave}} \right\}, \end{aligned} \quad (1)$$

which was once constructed by Novikov and Shifman to study $\psi' \rightarrow \pi^+\pi^-J/\psi$ transition [20]. In Eq. (1), the subscripts, S-wave and D-wave, represent the corresponding amplitudes

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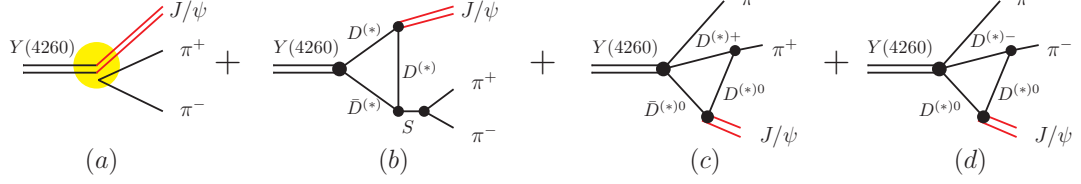


FIG. 1: (Color online.) The typical diagrams depicting $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$ decay. Here, Fig. 1 (a) denotes $Y(4260)$ direct decay into $J/\psi \pi^+ \pi^-$; Fig. 1 (b) describes the intermediate hadronic loop contribution to $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$. Fig. 1 (c) and (d) are from the ISPE mechanism.

from S-wave and D-wave contributions, respectively. $\Delta M = m_{Y(4260)} - m_{J/\psi}$ is the mass difference between $Y(4260)$ and J/ψ . $q^2 = (p_1 + p_2)^2 = m_{\pi^+ \pi^-}^2$ denotes the invariant mass of $\pi^+ \pi^-$ while θ is the angle between $Y(4260)$ and π^- in the $\pi^+ \pi^-$ rest frame. In addition, the pion mass and decay constants are taken as $m_{\pi^\pm} = 139$ MeV and $f_\pi = 130$ MeV, respectively. In the direct decay process, two free parameters, F and κ , are introduced, which can be determined by fitting to the experimental data.

The second mechanism in the $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$ decay is due to intermediate $S = \sigma(600)$ and $f_0(980)$ contributions, where the hadronic loop constructed by the charmed mesons is the bridge to connect $Y(4260)$ with $J/\psi S$ as described by Fig. 1 (b). In this work, we parameterize the decay amplitude corresponding to Fig. 1 (b) as

$$\mathcal{M}_S[Y(4260) \rightarrow \pi^+ \pi^- J/\psi] = \epsilon_{Y(4260)}^\mu \epsilon_{J/\psi}^\nu g_{\mu\nu} \frac{F_S}{(p_1 + p_2)^2 - m_S^2 + im_S \Gamma_S}, \quad (2)$$

where a subscript S can be taken as σ or $f_0(980)$ and m_S and Γ_S are the resonance parameters of $\sigma(600)$ and $f_0(980)$. Since the total decay width and mass of $\sigma(600)$ are of the same order, the minimal width approximation is not valid. Here, we adopt the momentum dependent decay width in the propagator of $\sigma(600)$, i.e.,

$$\Gamma_\sigma(m_{\pi^+ \pi^-}) = \Gamma_\sigma \frac{m_\sigma}{m_{\pi^+ \pi^-}} \frac{|\vec{p}(m_{\pi^+ \pi^-})|}{|\vec{p}(m_\sigma)|}, \quad (3)$$

where $|\vec{p}(m_{\pi^+ \pi^-})| = \sqrt{m_{\pi^+ \pi^-}^2/4 - m_\pi^2}$ is the value of pion momentum and $|\vec{p}(m_\sigma)|$ is the pion momentum with on-shell σ meson. In Eq. (2), two fitting parameters F_σ and $F_{f_0(980)}$ are introduced.

Besides these two decay mechanisms mentioned above, there is the third mechanism of $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$ decay, i.e., the ISPE mechanism, via which the typical diagrams depicting $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$ decay are given in Figs. 1 (c) and (d) corresponding to the π^- and π^+ emissions from $Y(4260)$, respectively. Through the ISPE mechanism, $Y(4260)$ first decays into a pair of intermediate charmed and anti-charmed mesons with initial single pion emission. Due to the continuous energy distribution of this pion, the intermediate charmed and anti-charmed meson pair is of low momentum, which makes them easily interact with each other to transform them into J/ψ and π .

The detailed calculations of $Y(4260) \rightarrow \pi^+ \pi^- J/\psi$ via the ISPE mechanism are presented in Ref. [2], which shows that there are charged enhancement structures near $D\bar{D}^*$ and $D^* \bar{D}^*$ thresholds. After performing the loop integrals, the decay amplitudes via the intermediate $D\bar{D}^* + h.c.$ and $D^* \bar{D}^*$ can be parameterized as

$$\begin{aligned} \mathcal{M}_{\text{ISPE}}^{D\bar{D}^*}[Y(4260) \rightarrow \pi^+ \pi^- J/\psi] &= g_{Y(4260)D^*D\pi} \epsilon_{Y(4260)}^\mu \epsilon_{J/\psi}^\nu \left[A_0 g_{\mu\nu} + (B_1 p_{1\mu} p_{1\nu} \right. \\ &\quad \left. + B_2 p_{1\mu} p_{2\nu} + B_3 p_{2\mu} p_{1\nu} + B_4 p_{2\mu} p_{2\nu}) \right], \end{aligned} \quad (4)$$

$$\begin{aligned} \mathcal{M}_{\text{ISPE}}^{D^*\bar{D}^*}[Y(4260) \rightarrow \pi^+ \pi^- J/\psi] &= g_{Y(4260)D^*D^*\pi} \epsilon_{Y(4260)}^\mu \epsilon_{J/\psi}^\nu \left[A'_0 g_{\mu\nu} + (B'_1 p_{1\mu} p_{1\nu} \right. \\ &\quad \left. + B'_2 p_{1\mu} p_{2\nu} + B'_3 p_{2\mu} p_{1\nu} + B'_4 p_{2\mu} p_{2\nu}) \right], \end{aligned} \quad (5)$$

respectively, where the coefficients $A_i^{(\prime)}$ and $B_i^{(\prime)}$ ($i = 1 \sim 4$), in front of the different Lorentz structures can be evaluated by the loop integrals in the ISPE mechanism (see Ref. [2] for more details). As indicated in Ref. [2], the coupling constants of $Y(4260)$ interacting with $D^{(*)}D^{(*)}\pi$, $g_{Y(4260)D^*D\pi}$ and $g_{Y(4260)D^*D^*\pi}$, are unknown and become fitting parameters.

The total decay amplitude of $Y(4260) \rightarrow \pi^+ \pi^- J/\psi$ is the sum over the subamplitudes, i.e.,

$$\begin{aligned} \mathcal{M}^{\text{Total}}[Y(4260) \rightarrow \pi^+ \pi^- J/\psi] &= \mathcal{M}_{\text{Direct}} + e^{i\phi_\sigma} \mathcal{M}_\sigma + e^{i\phi_{f_0(980)}} \mathcal{M}_{f_0(980)} \\ &\quad + e^{i\phi_{\text{ISPE}}} (\mathcal{M}_{\text{ISPE}}^{D\bar{D}^*} + \mathcal{M}_{\text{ISPE}}^{D^*\bar{D}^*}), \end{aligned} \quad (6)$$

where three phase angles ϕ_σ , $\phi_{f_0(980)}$ and ϕ_{ISPE} are introduced.

As discussed above, in our scenario we introduce nine free fitting parameters as

$$F, \kappa, F_\sigma, F_{f_0(980)}, \phi_\sigma, \phi_{f_0(980)}, \phi_{\text{ISPE}}, g_{Y(4260)D^*D\pi}, g_{Y(4260)D^*D^*\pi},$$

which are determined by fitting to the experimental data.

With the above preparation, the differential decay width of $Y(4260) \rightarrow \pi^+ \pi^- J/\psi$ is

$$\begin{aligned} d\Gamma(Y(4260) \rightarrow \pi^+ \pi^- J/\psi) &= \frac{1}{3} \frac{1}{(2\pi)^3} \frac{1}{32m_{Y(4260)}^3} |\mathcal{M}^{\text{Total}}|^2 dm_{J/\psi\pi}^2 dm_{\pi\pi}^2, \end{aligned} \quad (7)$$

where $m_{J/\psi\pi}^2 = (p_2 + p_3)^2$ and $m_{\pi\pi}^2 = (p_1 + p_2)^2$. Using Eq. (7), we can obtain the theoretical distributions of the $J/\psi \pi^\pm$ and

$\pi^+\pi^-$ invariant mass spectra, which will be applied to fitting to the BESIII data [1]. Additionally, the resonance parameters involving in our calculation are listed in Table I.

TABLE I: The resonance parameters (in units of GeV) used in present work. The resonance parameters of $\sigma(600)$ are taken from Ref. [21] and the other resonance parameters are from PDG [22].

Parameter	value	Parameter	value	Parameter	value
$m_{Y(4260)}$	4.263	$m_{J/\psi}$	3.097	m_{π^\pm}	0.139
m_σ	0.513	Γ_σ	0.335		
$m_{f_0(980)}$	0.980	$\Gamma_{f_0(980)}$	0.070		

At present, BESIII has not only given the $J/\psi\pi^\pm$ invariant mass distributions but has also provided the $\pi^+\pi^-$ invariant mass spectrum [1]. This information provides us good chance to test the ISPE mechanism. With Eq. (7) and the help of the MINUIT package, we carry out the global fit to the BESIII data of $Y(4260) \rightarrow \pi^+\pi^- J/\psi$, which is helpful to answer the question whether the $Z_c(3900)$ structure observed by BESIII can be reproduced by the ISPE mechanism, where we also consider the interference effects of the ISPE mechanism with other two decay mechanisms. We fit the $d\Gamma(Y(4260) \rightarrow \pi^+\pi^- J/\psi)/dm_{J/\psi\pi^\pm}$ and $d\Gamma(Y(4260) \rightarrow \pi^+\pi^- J/\psi)/dm_{\pi^+\pi^-}$ distributions with the experimental data.

TABLE II: The obtained values of the fitting parameters for the best fit to the BESIII data of $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ decay [1].

Parameter	Value	Parameter	Value
F	24.30 ± 6.05	κ	0.25 ± 0.15
f_σ	$190.27 \pm 28.35 \text{ GeV}^2$	ϕ_σ	-1.09 ± 0.51
$f_{f_0(980)}$	$83.56 \pm 11.54 \text{ GeV}^2$	$\phi_{f_0(980)}$	-2.52 ± 0.23
$g_{Y(4260)D^*\pi}$	25.26 ± 1.88	$g_{Y(4260)D^*D^*\pi}$	$-2.30 \pm 1.11 \text{ GeV}^{-1}$
ϕ_{ISPE}	2.87 ± 0.30		

The values of the fitting parameters obtained are listed in Table II. The corresponding best fit to the $J/\psi\pi^\pm$ and $\pi^+\pi^-$ invariant mass distributions is shown in Fig. 2. Comparing our theoretical results with the BESIII data, we notice that the $d\Gamma(Y(4260) \rightarrow \pi^+\pi^- J/\psi)/dm_{J/\psi\pi^\pm}$ distributions well agree with the $J/\psi\pi^\pm$ invariant mass spectra. Here the $Z_c(3900)$ structure and its reflection can be nicely reproduced, where our fitting results indeed reflect the fact that $Z_c(3900)$ is much sharper than its reflection. In addition, with the same fitting parameters, the theoretical distribution of $d\Gamma(Y(4260) \rightarrow \pi^+\pi^- J/\psi)/dm_{\pi^+\pi^-}$ is also given, which can well reproduce the BESIII data of the $\pi^+\pi^-$ invariant mass spectra again.

In summary, the charged charmonium-like structure $Z_c(3900)$ has been newly observed and reported by the BESIII Collaboration [1] and confirmed by Belle [14] and CLEO-c

[15]. After this new observation, different theoretical groups have given different explanations to $Z_c(3900)$ [5–12]. Among these explanations, the discussions on whether the structure of $Z_c(3900)$ is due to an exotic state or not are very popular, where the exotic state explanation of $Z_c(3900)$ includes molecular state composed of D and \bar{D}^* mesons or tetraquark state.

As mentioned in the BESIII experimental paper [1], there exist the theoretical predictions of charged charmonium-like structures near the $D\bar{D}^*$ threshold [2–4] before the observation of $Z_c(3900)$. In Ref. [2], the ISPE mechanism was applied to study $Y(4260) \rightarrow \pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi'$, $\pi^+\pi^-h_c$ decays, where two of the authors of this paper predicted the interesting phenomena of charged $D\bar{D}^*$ and $D^*\bar{D}^*$ structures existing in the $J/\psi\pi^\pm$, $\psi'\pi^\pm$ and $h_c\pi^\pm$ invariant mass spectra. The BESIII observation of $Z_c(3900)$ has inspired us to study the $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ decay process by the ISPE mechanism again together with other diagrams shown in Figs. 1, where we are able completely to fit our model including a tree diagram as well as relative phases to the experimental data in our scenario since BESIII now provides abundant information of the distribution of the $J/\psi\pi^\pm$ and $\pi^+\pi^-$ invariant mass spectra.

As shown in Fig. 2, the $Z_c(3900)$ structure has been remarkably reproduced under the ISPE mechanism that includes the interference effects. This fact affirmatively answers whether $Z_c(3900)$ corresponds to the predicted charged charmonium-like structure near $D\bar{D}^*$ threshold via the ISPE mechanism in Ref. [2].

Besides the prediction and/or reproduction relevant to $Z_c(3900)$ under the ISPE mechanism, there are other abundant predictions on the features of charged enhancement structures in the hidden-charm dipion decays of higher charmonia [2], the hidden-bottom dipion decays of $\Upsilon(11020)$ [18], and the hidden-strange dipion decays of $Y(2175)$ [19]. We hope that future experiments will carry out search for these novel phenomena.

Given the experimental data, the present work has provided an important approach to test the ISPE mechanism. With more experimental observations, more phenomenological and theoretical efforts should be made by combining further experimental data, which will finally clarify what is the underlying mechanism behind the observed $Z_c(3900)$ structure and other exotic structures.

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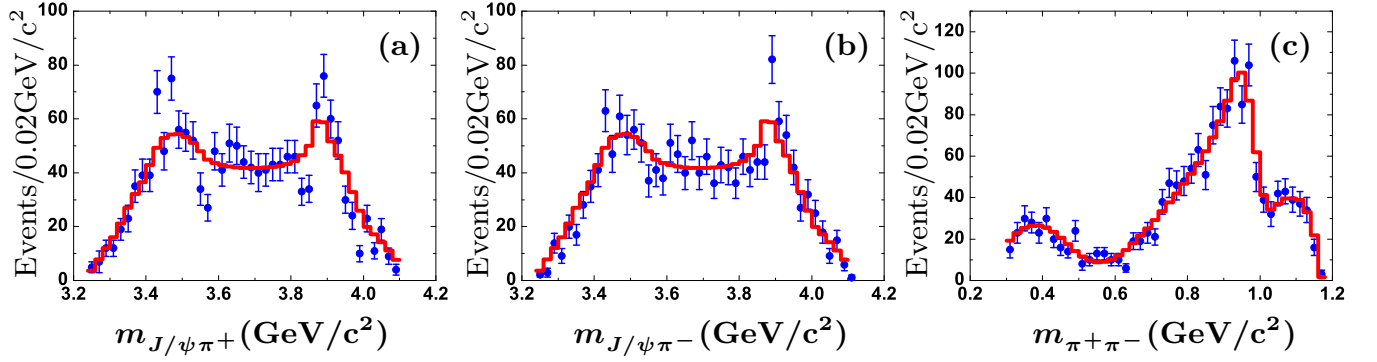


FIG. 2: (color online). The distributions of the $J/\psi\pi^+$, $J/\psi\pi^-$ and $\pi^+\pi^-$ invariant mass spectra of $Y(4260) \rightarrow \pi^+\pi^- J/\psi$. The blue dots with error bars are the experimental data given by BESIII [1], while the red histograms are the best fit by our model considering the ISPE mechanism contribution to the $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ decay.

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